Acute Glucose Response to Maximal Exercise is Associated with Cardiorespiratory Fitness and Heart Rate Variability in Healthy Subjects

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Abstract

High-intensity exercise acutely elevates blood glucose levels, yet the underlying links between this acute glycemic surge, cardiorespiratory fitness, and cardiac autonomic regulation remain unclear. We investigated whether an acute post-exercise glucose increase (ΔCGM >2 mmol/L) during cardiopulmonary exercise testing (CPET) reflects specific fitness, autonomic, and glycemic characteristics. Using continuous glucose monitoring and single-lead ECG data from 47 healthy active adults (BUT CGM dataset), participants were categorized into a glucose increase (n = 20) and a non-increase group (n = 27) based on the glycaemia response to GET (ΔCGM). Linear mixed-effects models were applied to evaluate multi-day glycemic variability and multi-night nocturnal heart rate variability (HRV). The glucose increase group demonstrated significantly higher VO2max, greater pre-exercise SDNN and total power, lower nocturnal HR, and elevated nocturnal pNN50, lnRMSSD, and total power. Glycemic variability across four days was also higher in the increase group. Crucially, no group × time interactions were significant for nocturnal HRV or glycemic variability, indicating that these differences were stable traits present prior to exercise rather than transient post-test perturbations. In conclusion, the acute glucose excursion during maximal exercise identifies a stable, individual-level metabolic–autonomic phenotype rather than a simple acute stress response.

1. Introduction

High-intensity exercise can transiently increase blood glucose levels in healthy non-diabetics [1,2]. This exercise-induced hyperglycemia is caused by increased demand for glucose as a source of energy [3,6]. Magnitude of this response varies between individuals and may reflect differences in metabolic capacity and training status [4].

Cardiorespiratory fitness, measured by maximal oxygen consumption (VO_2max), is a strong predictor of metabolic health. Heart rate variability (HRV), a non-invasive marker of autonomic nervous system (ANS), provides complementary information about the sympathovagal balance [5,9]. Recent studies have suggested that endurance-trained athletes may exhibit greater glucose excursions during high-intensity exercise [2]. However, the relationship between the acute glucose response, glucose dynamics and cardiac autonomic function during after-exercise days has not been systematically investigated. Previous studies examined either glucose responses to exercise [2] or HRV changes around exercise [5,7] separately. To our knowledge, this is the first study combining continuous glucose monitoring with multi-day HRV assessment around maximal exercise testing.

The aim of this study was to determine whether an acute glucose increase exceeding 2 mmol/L during high-intensity exercise is associated with (1) cardiorespiratory fitness, (2) glycaemic variability in the days before/after the test, (3) pre- and post-exercise cardiac autonomic modulation, and (4) nocturnal cardiac autonomic modulation in the days before/after the test.

2. Methods

2.1. Study design and participants

The data from the Brno University of Technology Continuous Glycaemia, ECG, Activity and Food Intake Database (BUT CGM) was used. From the whole database including data from 60 healthy active adults, 47 were used in this study due to the presence of all necessary data (age 25.3±6.1 years, 33 males, 14 females, BMI 23.3±2.5 kg/m²). Each participant wore a continuous glucose monitoring (CGM) device (Dexcom G7) recording interstitial glucose every 5 minutes for approximately 10 days. Simultaneously, a single-lead electrocardiogram (ECG) was recorded using Bittium Faros 180 device with

sampling rate of 1,000 Hz. The study was approved by the Ethics Committee of the Centre of Sports Activities, Brno University of Technology, on January 10, 2025 (IRB Protocol reference number EK:1/2025). Informed written consent was obtained from all participants.

2.2. Cardiopulmonary exercise testing

Each participant performed a Cardiopulmonary Exercise Testing (CPET) using the Graded Exercise Test (GET) on a bicycle ergometer or treadmill with breath-by-breath gas exchange analysis. The protocol consisted of a 5min warm-up, stepwise workload increase every 2 min until exhaustion, and a 5min cooldown (total length was 20–30 min). Maximal oxygen consumption (VO_2max) was determined as the highest 30s average normalized to body weight (ml/min/kg).

2.3. Glucose response assessment

The glycaemia response to GET (ΔCGM) was quantified as the difference between the maximum interstitial glucose concentration in the post-exercise window (10 min before CPET end to 10 min after CPET end; counting with 10 min CGM latency) and the minimum interstitial glucose concentration in the pre-exercise window (20 min before CPET start to CPET start). According to ΔCGM value, participants were divided into two groups: glycaemia increase group (ΔCGM > 2 mmol/L) and no-increase group (ΔCGM ≤ 2 mmol/L). This cutoff was chosen considering the measurement accuracy of the Dexcom G7 (MARD ~8–9%), to ensure the observed increase exceeds expected measurement variability and represents a true increase of min. 1 mmol/L.

Glycaemia variability was assessed using the coefficient of variation (CV [%]), standard deviation (SD [mmol/L]), mean amplitude of glycemic excursions (MAGE [mmol/L]), and mean glycaemia (MEAN [mmol/L]) for the day before, test day, and one and two days after the test (00:00 to 23:59).

2.4. HRV analysis

HRV was analyzed from RR intervals extracted from ECGs. Two 10-min segments were defined: pre-exercise (15 to 5 min before CPET start) and post-exercise (5 to 15 min after CPET end) [8]. Time-domain HRV features included mean heart rate (HR [bpm]), standard deviation of the NN intervals (SDNN [ms]), root mean square of successive differences between adjacent NN intervals (RMSSD [ms]), logarithm RMSSD (lnRMSSD [ms]), and the percentage of successive NN intervals that differ by more than 50 ms (pNN50 [%]). Frequency-domain HRV analysis was performed using Fast Fourier Transform (FFT) after 4 Hz resampling, yielding LF power (0.04–0.15 Hz, [ms^2]), HF power (0.15–0.4 Hz, [ms^2]), LF/HF ratio ([-]) and total power (TPOW [ms^2]) [9].

Nocturnal HRV was computed in 5min epochs across the sleep period and was averaged. The analysis window excluded the first and last hour of sleep to minimize confounding from sleep onset and offset. Four nights were analyzed: the night before the test (night-1), the night of the test day (night 0), and one and two nights after the test (night+1 and night+2, respectively).

2.5. Statistical analysis

We evaluated data normality using the Shapiro–Wilk test. To suit the distribution of variables measured once per participant (VO_2max, pre-/post-/pre-to-post exercise HRV), we used non-parametric tests: Mann–Whitney U tests for between-group comparisons, Fisher's exact test for sex distribution, and medians for descriptive reporting.

For continuous multi-day data, we applied a linear mixed-effects model (LMM) with a random participant intercept. This accounts for within-participant correlation across repeated nocturnal HRV (four nights) and glycaemic variability (four days) measurements while accurately capturing time-dependent group dynamics. A second LMM included a group × time interaction to formally test whether group differences vary across days or nights. To complement this, we used Friedman tests for within-group trajectories and Spearman correlations to analyze ΔCGM on a continuous scale without relying on a fixed cutoff.

3. Results

3.1. Participant characteristics

Of 47 participants, 20 (42.6%) exhibited ΔCGM > 2 mmol/L (mean ΔCGM = 3.14±0.76 mmol/L), while 27 (57.4%) did not (mean ΔCGM = 0.7±1.12 mmol/L). The groups did not differ in age (median 24 vs 23 years, $p = 0.368$), BMI ($p = 0.116$) or sex distribution (13 men / 7 women in increase group vs 20 / 7 in non-increase group, $p = 0.535$). The glycaemia increase group had significantly lower body mass (67.5 vs 79.0 kg, $p = 0.026$).

3.2. Cardiorespiratory fitness

The glycaemia increase group had significantly higher VO_2max (median 52.5 vs 45.0 ml/min/kg, $p = 0.009$). The Spearman correlation ($\rho = 0{,}416$, $p = 0{,}004$) confirms this.

3.3. Glycaemia variability

In the LMM, glycaemic variability was significantly higher in the glycaemia increase group averaged across the four days: CV, SD and MAGE; MEAN did not differ as

can be seen in Table 1. The effect of group × day interaction (all $p \geq 0.27$, Table 1) did not reach significance, and within-group change across the four days was absent in seven of the eight feature-by-group Friedman tests (all $p \geq 0.09$). The higher variability of the increase group was therefore already present on the day before the test and did not increase after it. This difference should, however, be treated as exploratory: it did not scale with the magnitude of ΔCGM. Pooled across the four days, glycaemic variability CV ($\rho = 0.107$, $p = 0.475$), SD ($\rho = 0.175$, $p = 0.240$), MAGE ($\rho = 0.242$, $p = 0.101$) and MEAN ($\rho = 0.192$, $p = 0.197$) was uncorrelated with ΔCGM.

Table 1: LMM – effect is the difference of the glycaemia increase group relative to the no-increase group, averaged over the four days, with a random participant intercept. The last column tests whether that difference varies across time points. *p < 0.05.

Feature	Group effect [95% CI]	p gr.	p gr. × time
CV [%]	+2.53 [0.76, 4.30]	0.005*	0.280
SD [mmol/L]	+0.17 [0.06, 0.27]	0.002*	0.271
MAGE [mmol/L]	+0.32 [0.12, 0.53]	0.002*	0.287
MEAN [mmol/L]	+0.16 [-0.13, 0.45]	0.284	0.828

3.4. HRV

As can be seen from Table 2, before exercise, the glycaemia increase group had significantly higher SDNN and TPOW. This is consistent with Spearman correlation between HRV features and ΔCGM, which is statistically significant only for SDNN ($\rho = 0.392$, $p = 0.007$) and TPOW ($\rho = 0.340$, $p = 0.022$).

Table 2: Between-group comparisons of HRV before and after GET and pre-to-post change (Mann–Whitney U test). Medians shown. *p < 0.05.

Feature	Inc > 2 mmol/L	NoInc	p-value
Pre-exercise			
HR [bpm]	91.9	103.1	0.153
SDNN [ms]	84.7	64.3	0.022*
RMSSD [ms]	30.0	22.6	0.159
lnRMSSD [ms]	3.40	3.12	0.159
pNN50 [%]	9.5	3.4	0.180
LF [ms²]	243.1	130.2	0.118
HF [ms²]	46.6	20.4	0.102
LF/HF [-]	6.01	6.13	0.723
TPOW [ms²]	908.2	377.4	0.010*
Post-exercise			
HR [bpm]	118.5	115.2	0.513
SDNN [ms]	41.9	43.2	0.816
RMSSD [ms]	10.0	17.8	0.113
lnRMSSD [ms]	2.30	2.88	0.113
pNN50 [%]	0.4	0.8	0.227
LF [ms²]	31.7	84.4	0.038*
HF [ms²]	4.7	19.8	0.007*
LF/HF [-]	7.93	3.83	0.011*
TPOW [ms²]	131.2	211.5	0.046*
Change (pre-to-post)			
ΔHR [bpm]	+27.6	+8.6	0.006*
ΔSDNN [ms]	−47.4	−13.1	0.058
ΔRMSSD [ms]	−13.8	−5.3	0.108
ΔpNN50 [%]	−8.2	−1.4	0.124
ΔLF [ms²]	−218.1	−83.3	0.090
ΔHF [ms²]	−38.9	−8.9	0.020*
ΔLF/HF [-]	+2.1	−0.7	0.045*
ΔTPOW [ms²]	−861.4	−193.6	0.002*

Post-exercise, the pattern reversed: the increase group showed lower LF, HF, and TPOW, but higher LF/HF ratio. The Spearman correlation shows no significant relationship for all features ($p > 0.110$).
The pre-to-post exercise changes in ΔHR, ΔHF, ΔLF/HF and ΔTPOW differed significantly between groups, being larger in the glycaemia increase group (Table 2). The Spearman correlation analysis shows significance in ΔTPOW ($\rho = -0.399$, $p = 0.010$), ΔHR ($\rho = 0.361$, $p = 0.014$), and ΔSDNN ($\rho = -0.312$, $p = 0.035$).

3.5. Nocturnal HRV

Averaged across the four nights, the glycaemia increase group showed lower HR and higher nocturnal cardiac autonomic modulation – lnRMSSD, pNN50, and TPOW. The remaining indices showed the same direction without reaching significance (Table 3). The effect of the group × night interaction (all $p \geq 0.19$) was not significant, and within neither group did nocturnal HRV change across the four nights (Friedman, all $p \geq 0.09$). The between-group difference was therefore present already on the night before the test and did not change after it.

Table 3: LMM – effect is the difference of the glycaemia increase relative to no-increase group, averaged over the four nights, with a random participant intercept. The last column tests whether that difference varies across time points. *p < 0.05.

Feature	Group effect [95% CI]	p gr.	p gr. × time
HR [bpm]	-5.4 [-9.8, -1.0]	0.015*	0.878
SDNN [ms]	+12.0 [-0.1, 24.1]	0.053	0.571
RMSSD [ms]	+11.8 [-3.6, 27.3]	0.134	0.726
lnRMSSD [ms]	+0.23 [0.02, 0.45]	0.035*	0.479
pNN50 [%]	+11.4 [2.7, 20.1]	0.010*	0.492
LF [ms²]	+62.0 [-34.7, 158.6]	0.209	0.687
HF [ms²]	+53.1 [-16.8, 123.1]	0.136	0.693
TPOW	+360 [32, 688]	0.031*	0.191

Nocturnal TPOW ($\rho = 0.380$, $p = 0.009$), LF ($\rho = 0.342$, $p = 0.020$), pNN50 ($\rho = 0.334$, $p = 0.023$), and HR ($\rho = -0.325$, $p = 0.028$) correlate significantly with ΔCGM. TPOW, pNN50 and HR show consistent results, however LF and lnRMSSD do not.

4. Discussion

This study shows that an acute glycaemia increase > 2 mmol/L during high-intensity exercise identifies a distinct participant profile: significantly higher cardiorespiratory fitness (VO2max), greater cardiac autonomic modulation both at rest (SDNN, TPOW) and during sleep (lnRMSSD, pNN50, TPOW), lower HR during sleep, and higher day-

to-day glycaemic variability (CV, SD, MAGE). LMMs showed these differences to be stable across the monitoring window with no group × time interaction significance.

The statement that fitter individuals show a greater glucose response is consistent with Flockhart et al. [2]. The higher resting SDNN and TPOW of the increase group is a recognized correlate of cardiovascular fitness [5,7].

Flockhart et al. [4] reported reduced glucose tolerance and insulin sensitivity in endurance athletes after prolonged exercise, indicating that glucose handling in trained individuals is sensitive to accumulated training load rather than being uniformly favourable. If the increase group in our study carries a higher habitual training load, for which its higher VO_2max is an indirect proxy, its elevated CV, SD and MAGE across all four days would be a chronic characteristic rather than an incidental one, and the absence of a group × day interaction is consistent with this. The present design cannot separate this from the simpler possibility that more highly trained participants consume more carbohydrate, since dietary intake was not considered. The central message of this analysis is therefore that the size of the glucose rise during a maximal exercise test is a property of the person rather than of the test.

Limitations: The groups differed in body mass, and the sex distribution (did not differ significantly between groups, $p = 0.535$). Dietary intake and activity after the test were not considered, so carbohydrate intake for glycogen restoration or further training cannot be excluded as contributors to the observed glycaemic variability. The CPET modality (cycle ergometer vs treadmill) was not balanced by design. Both may contribute to the observed fitness difference.

Possible use: These findings may have potential applications in sports diagnostics, where exercise-induced glucose responses could complement and possibly even predict established markers such as VO_2max and HRV in characterizing an individual metabolic–autonomic profile [4] and maybe vice versa (from test ECG predict glycaemia – useful for diabetics; needs to be further investigated). Future studies could include lactate measurements to investigate whether larger exercise-induced glucose excursions are accompanied by higher lactate responses during maximal exercise [10]. Such multimodal monitoring may improve interpretation of metabolic responses to training, although the practical value of CGM in athletes still requires further validation.

5. Conclusion

In healthy active adults, the magnitude of the acute glucose excursion during maximal exercise identifies a person-level profile rather than a response to the test itself. Participants with an increase > 2 mmol/L had higher VO_2max and greater cardiac autonomic modulation both before the test and across all four monitored nights, and the same associations held for ΔCGM analysed on its continuous scale. No group × time interaction was significant for any nocturnal HRV or glycaemic measure, indicating that this profile was already present before the test and did not change after it. A difference in day-to-day glycaemic variability was also observed, but it did not scale with ΔCGM and is reported as exploratory. A single CGM and ECG recording around one exercise test is therefore sufficient to describe a person-level metabolic–autonomic phenotype. Whether the glucose excursion carries information beyond established fitness measures remains to be determined.

Acknowledgments

This work was supported by Horizon KDT JU project DistriMuSe (grant agreement No. 101139769-2) and co-funded by the Ministry of Education, Youth and Sports of the Czech Republic (grant No. 9A24005).

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